The influence of imaging gradients in the analysis of diffusion signals from pulsed and oscillating gradient sequences

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Target audience: Those interested in modelling the diffusion signal measured with pulsed and oscillating gradient spin-echo sequences.

Purpose: Oscillating gradient spin-echo sequences (OGSE) [1,2] have the ability to measure diffusion over shorter time scales than conventional pulsed gradient spin-echo sequences (PGSE). As such, performing both OGSE and PGSE experiments extends the range of diffusion times that can be probed, providing, for example, access to microstructural information through measurements of the time-dependent diffusion coefficient [3,4]. Here we consider the influence that imaging gradients have when analysing data from OGSE and PGSE scans, extending the work of Mattiello et al. [5] to include the effects of imaging gradients on OGSE *b*-values. We then evaluate how parameters obtained from model fitting to OGSE and PGSE data are affected if the influence of imaging gradients is ignored.

Methods: Following the method in [5] we calculate the diffusion-weightings produced by the interactions between all gradient pairs, with each diagonal element of the *b*-matrix calculated by summing the weighting from the appropriate interactions for that direction. By adding the diagonal elements of the *b*-matrix we obtain effective *b*-values for OGSE and PGSE sequences, which can then be compared to *b*-values calculated if only the diffusion gradients are considered.

To evaluate how model parameters are affected if the diffusion-weighting introduced by imaging gradients is ignored, synthetic signals were generated according to three models commonly used in diffusion analysis: monoexponential decay, biexponential decay, and the kurtosis model. These signals were generated using *b*-values which account for the diffusion-weighting from imaging gradients, but were then fit to their respective models using *b*-values which did *not* account for imaging gradients. This was done for a range of ground truth parameters for each model, with the fitted values then compared to the ground truth. By doing this for OGSE and PGSE sequences, the impact imaging gradients have in the analysis of data from both sequences can be compared.

Results and discussion: Interactions between oscillating gradients and slice select, dephasing, slice refocusing, crusher, readout and phase-encoding gradients produce no diffusion-weighting, unlike in PGSE sequences. Figure 1 shows the percentage difference between *b*-values calculated with and without accounting for imaging gradients, for OGSE and PGSE sequences. We can see that OGSE *b*-values are affected less than PGSE *b*-values, and that lower *b*-values are affected more than higher ones. The 100% difference at $b = 0$ s/mm^2 shows that imaging gradients always introduce some diffusion-weighting, though with the parameters used here it is still very close to zero (b<0.14 s/mm^2); note that this is not always the case, and that for stimulated-echo sequences the diffusion-weighting introduced by imaging gradients can significantly increase the *b*-value of a supposedly $b = 0$ s/mm^2 scan [6].

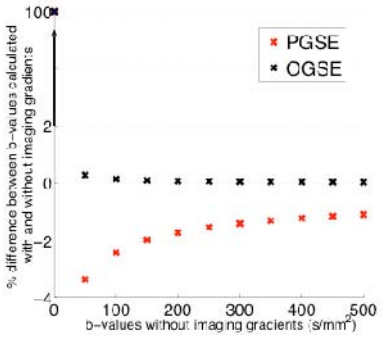

Figure 1. Percentage difference between *b*-values calculated with and without imaging gradients, for PGSE (red) and OGSE (black).

Apparent diffusion coefficients (ADCs) over a range of ground truth values up to 3.5x10^{-3} mm^2/s were used to assess the influence of imaging gradients when fitting to a monoexponential decay. The percentage difference between fitted and ground truth ADCs was negligible for OGSE sequences and <1.5% for PGSE sequences, indicating that accounting for imaging gradients has little affect when fitting to a monoexponential decay.

Figure 2 shows the percentage difference between fitted and ground truth values of D_1 for the biexponential model, for OGSE (left) and PGSE (right) sequences over a range of ground truth model parameters; D_1 and D_2 are compartmental diffusion coefficients and f_1 is the volume fraction of the first compartment. Over a range of ground truth parameters, errors are negligible for OGSE sequences while significant errors are introduced for certain parameter combinations in PGSE sequences; note the difference in colour scales for the two plots. For the kurtosis model, OGSE sequences give errors <0.01% and <3% for the diffusion coefficient, *D,* and kurtosis, *K,* respectively (over a range of ground truth *D* and *K* up to 3.5x10^{-3} mm^2/s and 2, respectively). For the same range, PGSE errors are <3% for *D*, while errors in *K* range from <0.1% to >10%, depending on the ground truth *D*-*K* combination; see Figure 3.

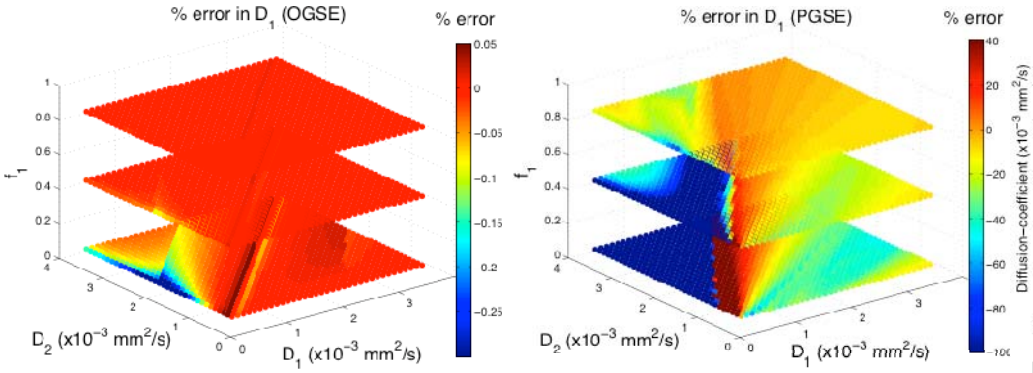

Figure 2. Percentage errors in fitted D_1 values as a function of ground truth biexponential parameters for OGSE (left) and PGSE (right).

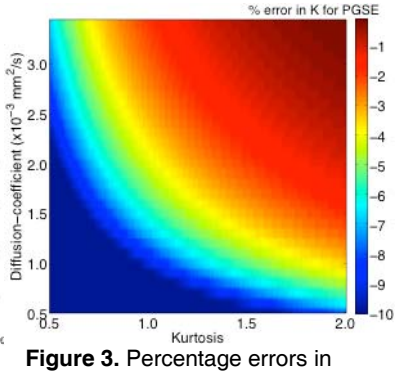

Figure 3. Percentage errors in fitted *K* values as a function of *D* and *K* ground truths, for PGSE.

Conclusions: The diffusion-weighting introduced by imaging gradients in OGSE sequences has been shown to have little impact on fitted parameters in a range of models, over a range of ground truth parameters. Conversely, neglecting imaging gradients for PGSE sequences can lead to significant errors in parameter estimates, particularly in biexponential fitting. Future work will examine how the presence of noise affects these results.

References: [1] Stepišnik J. *Physica B* 1981; 104:350-364. [2] Parsons EC, Does MD, Gore JC. *MRM* 2006; 55:75–84. [3] Fieremans E, Novikov DS, Sigmund EE, Liu K, Jensen JH, Helpern JA. *ISMRM* 2011; 19:1153. [4] Portnoy S, Flint JJ, Blackband SJ, Stanisz GJ. *MRM* 2012; doi: 10.1002/mrm.24325. [5] Mattiello J, Basser PJ, Bihan DL. In Bihan DL, ed. New York: Raven Press; 1995: 77-99. [6] Alexander DC, Dyrby TB. *ISMRM* 2012; 20:1884. **Acknowledgments:** AstraZeneca and MRC for funding.